UV-B Optical Depths at Mauna Loa: Relative Contribution of Ozone and Aerosols

PATRICK J. NEALE, DAVID L. CORRELL, VERNON R. GOODRICH, AND DOUGLASS R. HAYES, JR.

Smithsonian Environmental Research Center, Edgewater, Maryland 21037

Our laboratory has been monitoring surface spectral UV-B irradiance at Mauna Loa since fall of 1984. The instrument is similar to a radiometer in operation in Edgewater, Maryland [*Correll et al.*, 1992]. The instrument measures UV-B irradiance in a series of eight, 5-nm band passes (290-325 nm) and records 1-minute averages. Operation is continuous except for an annual break of about 1 month when the instrument is returned to Maryland for calibration. Our primary objective is to monitor long-term changes in incident solar UV-B irradiance. To accomplish this, a complete review of instrument calibrations over the period of operation is underway. Publication of our UV-B record will await the completion of this review.

While a record of absolute irradiance is presently not available, we nevertheless undertook preliminary analyses to assess the utility of the data set in regard to increasing our understanding of how different atmospheric factors control the intensity of surface UV-B. This was accomplished by calculating a relative optical depth for UV-B irradiance and statistically analyzing the relationship between such optical depth and parallel records of primary properties affecting atmospheric transparency to UV-B: total column ozone and aerosol optical depth.

Sunphotometers are commonly used for measurements of total optical depth, but usually are not designed to operate in the UV-B spectral region. On the other hand, the SERC radiometer measures total global irradiance as opposed to direct normal beam irradiance that is typically used for calculation of optical depth via Beer's law. Even so, an approximate optical depth can be estimated using the relationship:

$$I(\lambda) = I_0(\lambda) \cos(\theta_s) \exp(-\tau \sec \theta_s) \qquad (1)$$

where $I(\lambda)$ is surface irradiance, $I_0(\lambda)$ is direct normal irradiance at the top of the atmosphere, θ_s is the solar-zenith angle, and τ is total optical depth. Operationally, τ can be estimated as the slope of a linear regression of $log(I(\lambda)/cos(\theta_s))$ on $sec\ \theta_s$. Since the diffuse (sky) component of $I(\lambda)$ does not completely obey eq. (1) [*Box and Deepak,* 1979], the regression slope is termed "relative optical depth." The differences between relative and true optical depth are further discussed below.

For the analysis we chose measurements from morning to midday, for $\theta_s < 54°$. The analysis was done on days for which (1) morning to midday data were recorded, (2) clear sky conditions prevailed, (3) aerosol optical depth (τ_a) at 500 nm was measured (data kindly

provided by CMDL and further described in *Dutton et al.* [1994]), and (4) total column ozone was measured on the same day or day immediately before and after, i.e., by the MLO Dobson spectrometer. If ozone was not measured on the same day, it was estimated by interpolation. Clear sky conditions were ascertained by the lack of deviations from a log-linear relationship, additionally τ_a at 500 nm was generally only estimated for clear sky mornings [*Dutton et al.*, 1994]. No slope was estimated unless at least 50 1-minute averages could be entered into the regression analysis.

We focused on two parts of the record with contrasting conditions in terms of aerosol optical depth, a period from mid-1984 through 1985 when aerosol optical depth was low, i.e., near historic background levels, and 1991 through mid-1992 during which aerosol turbidity markedly increased due to the eruption of Mt. Pinatubo [*Dutton et al.*, 1994]. A total of 208 days during these two periods met the criteria for analysis.

A time-series of regression slopes for channels with nominal center wavelengths between 300 and 325 nm is shown in Figure 1. The results show several expected features for UV-B optical depths. First, optical depths vary by almost an order-of-magnitude over this spectral range with the largest depths associated with the shortest wavelengths. Second, there is significant seasonal variation of about 20-30% around the annual mean that is in phase with the seasonal variation in total ozone concentration (data not shown). Third, optical depths increase following the eruption of Mt. Pinatubo in June 1991 cf. [*Dutton et al.*, 1994].

The quantitative relationship between our estimated relative optical depth, ozone, and aerosol turbidity was analyzed via multiple linear regression. This is based on the assumption that total optical depth is the sum of components due to Rayleigh scattering, ozone, and aerosols, the last two components being time variable. By analogy, relative optical depth would be explained by the model:

$$\tau_\rho = A[O_3] + B\tau_a + C \qquad (2)$$

where τ_ρ is relative optical depth, $[O_3]$ is total column ozone and τ_a is aerosol turbidity at 500 nm, and $A, B,$ and C are constants. The results of the regression analysis applied to τ_ρ estimated from the 1984-1992 SERC UV-B radiometer record are given in Table 1. The proportion of variation in τ_ρ explained by the regression varied from 50% at 325 nm to 77% at 305 nm. All regressions were highly statistically significant, and all coefficients were significantly
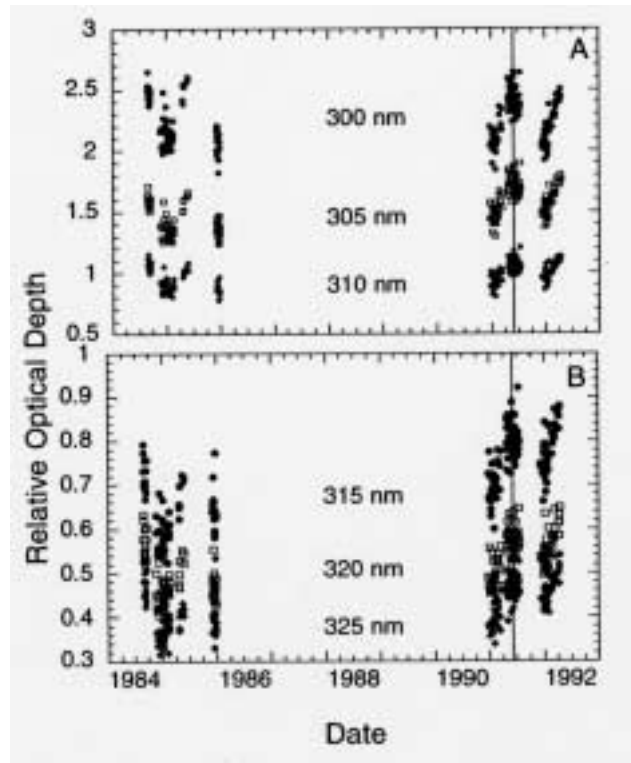
Fig. 1. Time series of relative optical depths in six UV-B bands (5 nm full bandwidth at half maximum) as estimated from morning-midday data recorded on the SERC UV-B radiometer. Upper (A) graph for 300-, 305-, and 310-nm bands, bottom (B) graph for the 315-, 320-, and 325-nm bands. Note the different abscissa scales. Although data has been recorded more-or-less continuously since 1984, only periods between 1984-1986 and 1991-1992 were used in the present analysis. Vertical line indicates date of Mt. Pinatubo eruption.

TABLE 1. Results of Regression Analysis of t_r Using Eq. 2

λ	a_{ol}	A	B	C	R^2
300.6	9.34	6.17	NS	0.63	68
304.8	5.42	5.04	0.76	0.19	77
310.7	2.45	2.72	0.51	0.24	66
314.6	1.46	2.66	0.66	0.08	63
320.1	0.68	1.45	0.43	0.13	57
325.2	0.33	1.12	0.38	0.12	50

Wavelength (λ) is the computed center wavelength for the band interference filter. a_{ol} is the absorption coefficient for total column ozone (units, atm^{-1} cm at NTP). A, B, and C are the fitted coefficients of eq. 2, and R^2 is the coefficient of determination (given in %). Ozone absorption is estimated from the spectral integrals of *Molina and Molina* [1986] assuming a stratosphere temperature of -40°C and normal surface temperature of 18°C. All regressions were significantly different from zero, n = 208. NS = not significant.

different from zero, except for the coefficient of τ_a for τ_ρ at 300 nm. The coefficient A is analogous to $a_{o\lambda}$, the spectral absorption coefficient for ozone. Estimates for the coefficient A were approximately equal to or exceeded effective $a_{o\lambda}$, Table 1, [*Molina and Molina*, 1986], except at 300 nm. The estimate for A may generally be greater than $a_{o\lambda}$ when τ_ρ has been estimated from total (direct plus diffuse) irradiance. Attenuation of the diffuse component of $I(\lambda)$ will be over longer mean optical paths than for the direct beam irradiance, e.g., *Perliski and Solomon* [1993]. The estimate of A for the 300-nm channel may be less than $a_{o\lambda}$ at 300 nm due to the probable red-shift of effective center wavelength of this channel with respect to the filter center wavelength (300.6 nm) as discussed by *Correll et al.* [1992].

The coefficient B is interpreted as an overall proportion between τ_a at 500 nm and aerosol optical depth in each of the UV-B bands. Generally, aerosol optical depth obeys an inverse power law (Ångstrom)

relationship with wavelength, arising from a Junge-type size distribution of aerosols [*Ångstrom*, 1961]. Thus it may be surprising at first sight to find that estimated B in all bands is less than one. However, the variation of τ_a at MLO was dominated by Mt. Pinatubo stratospheric aerosols, at least during the selected period [*Dutton et al.*, 1994]. These aerosols were inferred to have a narrow size range, in contrast with the Junge-type distribution of background aerosols [*Dutton et al.*, 1994]. Furthermore, our regression analysis (eq. 2) does not explicitly consider that relative airmass (m_r) for aerosol attenuation will be decreased at the altitude of MLO. This was not attempted since we did not have a basis to estimate m_r, i.e., vertical distributions of aerosols. However, we would expect m_r to range between $sec\ \theta_s$ and $0.67\ sec\ \theta_s$, the latter being the altitude adjusted Rayleigh m_r using the expression of *Bird and Riordan* [1986].

Finally, the constant term in the regression model, C, represents all time-constant contributions to optical depth, primarily attenuation due to Rayleigh (molecular) scattering. However, the estimated Cs are very much lower than the theoretical Rayleigh contribution at these wavelengths [*Bird and Riordan*, 1986]. Again, this is expected since our estimation of τ_ρ includes diffuse irradiance, which mainly arises from Rayleigh scattering.

Overall, the results of the regression analysis conform to expectations given the approximate nature of the model. Thus we conclude that our record can provide an indication of the relative importance of ozone and aerosol variation in causing variations in incident solar UV-B. One quantitative indicator of the relative importance of these two variables is the proportion of variance in τ_ρ explained by each variable in the regression eq. (2). The fractional contribution of each factor was obtained by (1) performing a second regression including A but omitting B (i.e., the term for

τ_a); the R^2 of this equation is the variance explained by ozone alone, and (2) the difference between the former R^2 and the R^2 for the full equation is the variance explained by τ_a. Such a "step-wise" approach can be used because variations in ozone and aerosol optical depth in this record are not correlated. The results are shown in Figure 2. Aerosol optical depth is seen to have a significant, though secondary, contribution to UV-B optical depth with the importance of aerosols increasing (and importance of ozone decreasing) at the longer wavelengths. Between 315 and 325 nm, aerosol optical depth accounts for almost 20% of the variation in total optical depth at MLO.
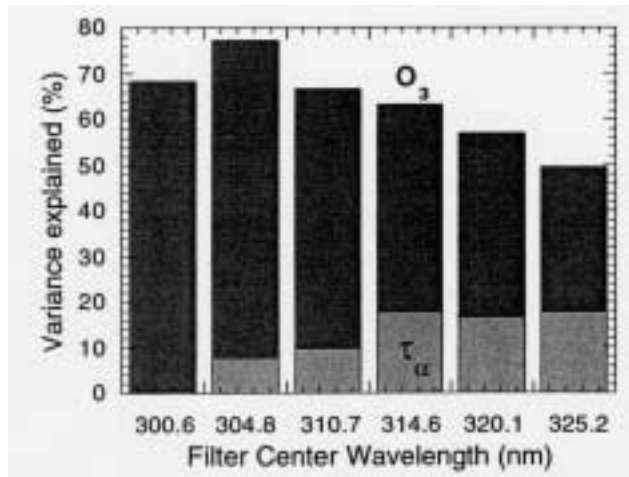
This preliminary analysis of our record of UV-B measurements at MLO suggests that volcanic aerosols can contribute significantly to the variation in UV-B irradiance. Aerosol-forced variation in UV-B is probably of less importance during periods inbetween eruptions, due to the high-altitude, pristine nature of the MLO site. These pristine conditions actually make it easier to detect an aerosol-related event when it does occur such as documented by [*Dutton et al.*, 1994]. An understanding of the interaction between aerosols, ozone, and UV-B will assist in the analysis of trends at sites with more complex variations in atmospheric conditions such as at our Maryland site. Thus in the future we will be extending this preliminary analysis over the complete MLO record.

Fig. 2. Partitioning of the total coefficient of determination (R^2) for the regression of relative optical depth against total column ozone and aerosol optical depth at 500 nm. The dark, upper bar is the variance explained by total column ozone; the light, lower bar is the variance explained by aerosol optical depth.

REFERENCES

Ångstrom, A., Technique of determining the turbidity of the atmosphere, *Tellus, 13*, 214-231, 1961.

Bird, R.E., and C. Riordan, Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the Earth's surface for cloudless atmospheres, *J. Clim. Appl. Meteorol., 25*, 87-97, 1986.

Box, M.A., and A. Deepak, Atmospheric scattering corrections to solar radiometry, *Appl. Opt., 18*, 1941-1949, 1979.

Correll, D.L., C.O. Clark, B. Goldberg, V.R. Goodrich, D.R. Hayes Jr., W.H. Klein, and W.D. Schecher, Spectral Ultraviolet-B radiation fluxes at the earth's surface: long-term variations at 39°N, 77°W, *J. Geophys. Res., 97*, 7579-7591, 1992.

Dutton, E.G., P. Reddy, S. Ryan, and J.J. DeLuisi, Features and effects of aerosol optical depth observed at Mauna Loa, Hawaii: 1982-1992, *J. Geophys. Res., 99*, 8295-8306, 1994.

Molina, L.T., and M.J. Molina, Absolute absorption cross sections of ozone in the 185- to 350- nm wavelength range, *J. Geophys. Res., 91*, 14,501-14,508, 1986.

Perliski, L.M., and S. Solomon, On the evaluation of air mass factors for atmospheric near-ultraviolet and visible absorption spectroscopy, *J. Geophys. Res., 98*, 10,363-10,374, 1993.